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Design Skills and Prototyping for Defense Systems

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Abstract

The armed forces of the U.S. military owe much of its competitive edge to the sophisticated design skills required to fashion complex integrated defense systems from advanced technologies. This study identifies the critical attributes of successful design team skills and the extent they are maintained through prototyping efforts. Defense system design and article prototyping have been proposed as a strategy to maintain the industrial base design skills while foregoing the expense and production engineering of full-scale system development and deployment. Studies of the design process and historical analyses of defense design are examined to identify the attributes of successful design teams and their skills. The engineering goals of prototyping and full-scale development efforts are discussed. A contrast is made with the skill development from full-scale system design, production, and deployment. The scope of the prototyping efforts is compared to the scope of full-scale system development. Design skills for prototyping and full-scale efforts are then compared, and an assessment is developed on the efficacy of prototyping to maintain necessary design skills. Implications for defense acquisition and engineering are discussed.

Introduction

The political and military environment after World War II laid down the architecture of a U.S. defense establishment that would endure for over 60 years and provide a relatively stable, if challenging, framework for developing and acquiring weapon systems. Despite its challenges, the current acquisition framework has consistently produced systems of clear technical superiority over almost all of its international competitors.

The performance gap between U.S. systems and the rest of the world is closing faster than at any point since the end of World War II. Near-peer U.S. competitors have apparently managed to replicate some of the most advanced U.S. capabilities (Majumdar, 2014). Senior leadership in the Department of Defense (DoD) is calling for a Long Range Research and Development Plan that will open new avenues of competitive advantage for U.S. armed forces. Similar efforts drove changes in strategic forces to nuclear weapons in the 1950s and advanced capabilities such as precision guided munitions and stealth in the 1970s (Hagel, 2014). Coupled with the steady implementation of the Better Buying Power initiatives (OUSD[AT&L], 2014), the expected end state is more efficient acquisition processes introducing a new wave of technology into weapons acquisition programs.

A prominent element of this strategy is the reliance on prototyping to maintain the development competency of industrial design teams. Such a strategy hinges on the assumption that design skills can be preserved through prototype development while avoiding the much larger cost of engineering development and production. The logic is appealing; however, the utility of prototyping has had a demonstrably mixed record in defense acquisition. Some programs, such as the Manhattan Project, were critically dependent on the engineering lessons of their prototype reactors (U.S. Department of Energy, 2010). In contrast, an analysis of the F-117 program indicates that, despite its

remarkable HAVE BLUE prototyping effort, the development timeline was about the same as its contemporaneous F-16 sister project (Smith, Shulman, & Leonard, 1996).

Understanding the complexities of this strategy requires an examination of three elements: (1) design as a cognitive activity in itself and traditional use of prototyping, (2) the record of defense prototyping, and (3) the viability of design teams. This analysis examines the relationship of these areas to overall systems development and prototyping and provides informed recommendations for a prototyping strategy.

Design Skills and Prototyping

The popular notion of the design process is one that begins at a high level of abstraction and ends in the technical details and processes of making a designed article. The design process is usually described as a series of sequential steps: (1) problem clarification, (2) conceptualizing (3) embodiments in layouts, and (4) elaboration and detailing (Eder, 1998). Academics and practitioners both use the mapping from the general to the specific alike, in part because it is readily understandable. One such depiction is given in Figure 1.

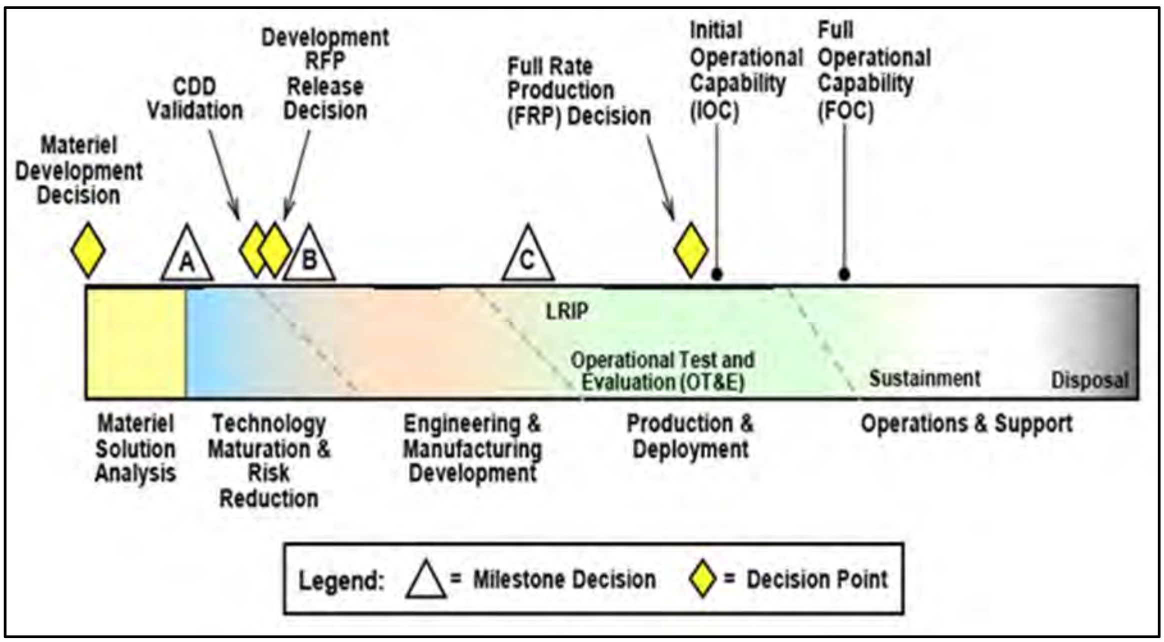

Figure 1. Development Model for Defense Acquisition Programs
(OUSD[AT&L], 2015)

Defense acquisition practitioners will recognize the acquisition model from the DoD 5000.02 “Operation of the Defense Acquisition System.” Milestones A, B, and C correspond roughly with Eder’s conceptualizing, embodiments/layout, and detail/elaboration steps, respectively. Prototyping activities are not explicitly called out in Figure 1—they are left to the discretion of the program manager.

Program managers with any experience know that the design process is rarely a steady progression through milestones or decision gates. Often the design process is full of blind alleys as designers work through technical challenges or adapt to changes in funding or schedule profiles. Less well understood is the nature of the design process itself. While it is modeled as a sequential exercise in problem analysis and solution synthesis, real designers work in a far more non-linear fashion that is dictated by experience, cognitive

framework, and specialized knowledge. These attributes are often key in determining the need, form, and function of a design prototype.

Designers at Work

Design is taught as a progression from the abstract to the concrete where a design challenge is bounded, requirements identified, the design problem decomposed, and its component parts analyzed. Once the design challenge is completely understood, solutions are generated, evaluated against requirements, and an overarching solution concept chosen. The selected concept is built out into greater and more concrete detail during functional and physical allocation of requirements and then implemented with physical assemblies.

NASA portrays this process as a cycle, with the finished product tested, evaluated, and lessons-learned applied to design modifications as appropriate. Figure 2 is an idealized diagram of the design process.

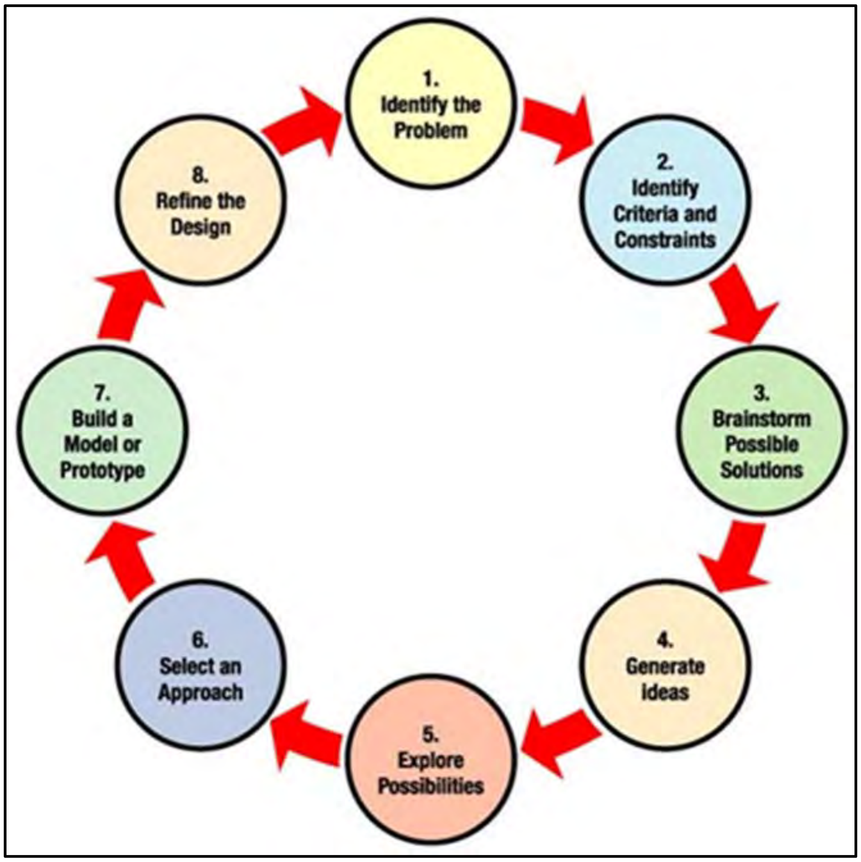

Figure 2. Idealized NASA Design Process
(NASA, 2008)

Prototyping is an integral part of the design process. Figure 2 is not specific about the type of prototype; however, the context implies a full-system prototype.

Studies of actual designers in action indicate a less systematic approach to design, particularly with 'ill-defined' problems (Cross, 2004; Guindon, 1990). Rather than the steady progression from abstract concept to physical implementation of Figure 2, designers will often opportunistically abandon the classic "breadth-first-then-depth" approach if a partial solution appears to fill a known niche in the solution space. Partial design solutions are built

out as far as needed, after which experienced designers often return to the higher-level problem decomposition—or move forward with a physical prototyping effort at the full- or sub-system level (Guindon, 1990). This "hop-scotching" among the various design steps can occur throughout the design process.

The seemingly haphazard execution of the design process at first appears inefficient, but in ill-defined or novel design challenges, it can be more efficient than a conventional breadth-to-depth approach. In novel design challenges, where there is no clear abstract-to-detail path, designers bring their own professional references and biases when mapping out the solution space. Experienced designers use partial solutions and relevant analogies not only as building blocks toward a comprehensive solution, but also as a way to bound the design problem and its analysis/decomposition (Kalogerakas, Luthje, & Herstatt, 2010; Spitas, 2011). The partial solutions become anchor points in the solution space for the final, comprehensive concept.

Practicing designers see design solutions coalesce around established, workable partial solutions rather than uniformly evolving from methodical solution generation. The role of the prototype is more complex than its depiction in Figure 2. The need for a prototype becomes less of a demonstration of a complete concept and more of a validation of contemplated, smaller scale partial solutions. As with known, validated partial solutions, this type of prototyping informs the design decomposition/analysis and maps the possible solution space.

The practice of the individual designer becomes more complex as multiple design specialties are combined to produce the large systems commonly associated with defense programs. Teams of designers produce more than physical systems. They also produce a wealth of tacit knowledge, experience, and approaches that are not only signature hallmarks of a design organization, but often unique to the team itself. How these teams become, and remain, viable influences the specific role of prototyping in the design process.

Design Teams

Defense systems are the product of industrial design teams. Since the end of World War II, the industrial design teams have been the bases on which are built the weapons systems of the U.S. Armed Forces. The defense industrial base of the immediate post-war period supported dozens of large and small companies producing basic technology to sophisticated large systems integration (Watts, 2008; Watts & Harrison, 2011). Through almost 70 years of rising and falling defense budgets since the end of World War II, the industrial base has gradually narrowed to a small number of large system integrators, 10–20 secondary vendors, and perhaps an equal number of tertiary companies whose primary business is defense articles, leading DoD senior leadership to launch a new round of technology offset to maintain U.S. technical supremacy (Hagel, 2014).

DoD leadership places a high priority on preserving design team skills without knowing exactly the critical attributes of their success. This leads to well-intentioned, but poorly informed, efforts to preserve production lines and design teams that maintain the status quo without effectively building a path to future technical developments that lead to the next generation of defense systems.

The quality and effectiveness of a design team are functions of a number of attributes. Studies indicate successful teams are: (1) experienced (Atman et al., 2007; Cross, 2001), (2) well-grounded in the system architecture under consideration (Brusoni & Prencipe, 2011; Henderson & Clark, 1990), (3) adept at using firm-specific knowledge to achieve competitive advantage (Lorell, Saunders, & Levaux, 1995), (4) active in designing systems and their components, (5) current on state-of-the-practice technology and

approaches, (6) intimately familiar with the design context and environment (Brusoni & Prencipe, 2001; Henderson & Clark, 1990), (7) composed of a "critical mass" of the design disciplines necessary to generate feasible design alternatives (Drezner et al., 1992), and (8) able to evaluate alternatives and find the most effective design with the lowest development risk (Atman et al., 2007; Cross, 2001).

The strategies of successful design teams mirror those of individual designers. Familiar design challenges invite known and proven solutions with implementations suitable for the design context. Complex design problems are approached with breadth-first decomposition with designers opportunistically deploying partial design solutions to aid further problem decomposition and build a comprehensive design solution. The advantage of a well-balanced and experienced design team is that it can draw from firm-specific knowledge to complement its general engineering and system knowledge to develop competitive solutions (Drezner et al., 1992; Lorell et al., 1995). General engineering knowledge of a design team informs its ability to produce a quality technical product, while its system knowledge narrows the team's specialty to, for example, bombers versus tactical aircraft. The firm-specific knowledge represents the way a design team envisions its solution and is based on its prior experience and accumulated, proprietary architectural knowledge. This is seen in the way certain design elements frequently recur in a company's product developments.

Firm-specific knowledge also informs a design team's strategy with respect to prototyping. Experience with developing specific types of systems bounds the design space through certain requirements, constraints imposed by the customer, and physics. The firm-specific knowledge imposes cognitive constraints and imperatives on the design teams on how the design space *should* be met in achieving a physical implementation of the design. The design team then deploys its development strategy, resulting in a variety of instantiations of prototype engineering. The next section examines the record of prototyping and its effectiveness in producing successful design outcomes.

Defense Prototyping

There are many different ways to define prototypes and prototype engineering. The following is a definition that can be used by the technologist and production engineer and strikes an appropriate balance:

> A prototype is a product (hardware and/or software) that allows hands-on testing in a realistic environment. In scope and scale, it represents a concept, subsystem, or production article with potential utility. It is built to improve the quality of decisions, not merely to demonstrate satisfaction of contract specifications. (Drezner, 1992, p. 9)

The lead production engineer for a tactical aircraft will have a different vision of a prototype than the lead technologist of a technical demonstrator project. Both professionals can effectively use prototyping. The former may use the prototyping effort to validate a design prior to production, while the latter may use a prototype to inform a pending design decision. Both uses are appropriate in the right context. Can the production engineer use an EMD prototype to inform design decisions? It is certainly possible—this is the acquisition strategy of the F-35 with its parallel design and production efforts. Can the technologist make production decisions from a technology demonstrator? This approach was used in the F-117 development. When the critical low-observable characteristics were understood and marginally producible, the aircraft was pushed into production (Smith et al., 1996). Both programs used their respective prototypes to inform subsequent decisions.

Prototyping has had a mixed history in defense acquisition programs, in part because the terms “prototype” and “prototyping” have never been defined in a consensus manner (Borowski, 2012). Researchers and practitioners alike have used a variety of definitions with varying scope. Most acquisition professionals have an intuitive feel for the attributes of a prototype and prototyping efforts, but they are usually informed by the context in which a prototype is executed. Not surprisingly, the value of prototyping is very much dependent on when and how a prototyping effort is initiated and structured, respectively.

Prototyping Value Added

The conventional wisdom regarding prototyping is that it is always beneficial and has positive influence on program outcomes. The extant studies on the value of defense prototyping indicate a variety of program outcomes for programs that have used prototypes. Perhaps the most surprising observation is that program outcomes have only a weak relationship with prototyping efforts (Arena et al., 2006; Borowski, 2012; Drezner, 1992; Drezner & Huang, 2009). Cost and schedule growth of acquisition programs are as evident in programs with prototypes and prototype engineering as those without.

The weak relationship is counter-intuitive. The acquisition practitioner would maintain that prototyping is almost always a worthwhile risk reduction technique. Examining individual programs reveals that the scope and timing of prototyping efforts within a program greatly affect the value added by the prototyping effort (Drezner & Huang, 2009; Tyson et al., 1991). The type of prototype, and its timing within a program, affects its value added to the program outcome.

For the balance of this paper, prototype articles and engineering are classed as technology demonstrators (P_t), developmental prototypes (P_d), prototypes of subsystems (P_s), or the prototype of a whole system (P_{emd}). The designations P_t and P_d loosely equate to X- and Y-plane levels of design maturity. Subsystem prototypes, P_s are efforts restricted to a subset of a system architecture, for example aircraft avionics or ground vehicle suspension. The P_{emd} is a near-final system configuration and can be considered a very mature prototype that addresses the full spectrum of performance requirements.

The extant literature would indicated that the most effective prototyping efforts are those that are launched in the context of a known and stable knowledge of the end-state configuration (Borowski, 2012; Drezner, 1992). From a classic design standpoint, the problem has been completely decomposed, technical challenges properly identified, and a comprehensive concept developed. Subsystem prototypes (P_s) contribute to the development of a technical demonstrator prototype (P_t) that focuses on a limited number of critical technical challenges. The technical resolutions and remaining requirements are incorporated into a developmental prototype (P_d). The lessons learned from P_d are reflected in P_{emd}. Table 1 summarizes this progression and integrates the design cycle of Figure 1 with the preceding discussion.

Table 1. Classic Design Engineering Prototyping

Design Phase	Goal	Prototyping	Remarks
Identify Problem	Translate problem statement into design space	Parametric analysis; models and simulation	Broad analysis of the problem
Identify constraints and requirements	Scope the design space	Parametric analysis; models and simulation	Critical technical areas identified; prototyping done with digital simulations and models
Idea generation	Breadth-first problem analysis and decomposition	Focused digital simulations of critical subsystems	Critical subsystem challenges identified; initial functional allocations developed
Evaluate ideas and select an approach	Feasibility evaluation with depth analysis of potential solutions; architectural and system selection	Subsystem prototypes - P_s	Key subsystem challenges identified; P_s developed at TRL 3–5
Model/Prototype	Specify and build an appropriate prototype for testing	Technology demonstrator prototype - P_t	P_s results integrated up to a P_t effort at TRL 5–6; "X-plane"
Refine design	Move design forward for production	Developmental prototype - P_d	P_t results integrated with more defined requirements to a P_d at TRL 6–8; "Y-plane"
Test/evaluate	Test of the EMD article	Production prototype - P_{emd}	Integration into a near-production end-item configuration; LRIP configuration

Table 1 outlines the situation where the end configuration, and, consequently, the instantiation of P_{emd}, is well defined. The evolution of the F-16 Falcon reflects the progression of Table 1. The P_{emd} configuration changed very little from the P_d, "Y-plane," prototype and resulted in a relatively trouble-free operational introduction and maintainability. The maintenance to flight hour ratio for the production aircraft was very similar to that of P_{emd} (Smith et al., 1996).

The F-16 prototyping approach serves well with a closed design process (D_c), where the P_{emd} has a well-understood configuration. Advancing prototype engineering where the end configuration is undefined, or open design (D_o), can have any number of unintended consequences. The early engineering for the F-117 stealth fighter focused almost entirely on an aircraft plan form optimized for low radar cross-section (RCS), even though the design was closed in the sense that the end configuration was known to be a manned penetrator aircraft. Once the low RCS performance was demonstrated, these key elements of the P_t were transitioned directly to P_{emd}. Key design elements that would have been demonstrated in a P_d, such as logistic support and maintainability, were notably absent. As a result, the maintenance of the F-117 per flight hour greatly exceeded the F-16 and other contemporary aircraft (Smith et al., 1996).

The designers of the first Plutonium production reactors faced a similar leap from P_t to P_{emd}, but within an open design, D_o, context. The end configuration was almost completely undefined. The first production reactors for the Manhattan Project suffered a near-catastrophic engineering design flaw stemming directly from the leap between P_t and P_{emd}. Enrico Fermi's Chicago Pile-1 (CP-1) demonstrated the first sustainable nuclear reaction in late 1942—the primary focus of the effort; however, the CP-1 did little to inform the P_{emd} for the DuPont designers charged with building a production reactor, other than demonstrating a sustainable chain reaction. The first production reactor, the Hanford B-Reactor, went

critical only to shut down within a few hours because of Xenon poisoning, a known by-product of nuclear fission. Fortunately, the DuPont engineers had built in extra critical capacity that enabled the design to successfully operate once the failure mechanism was understood. Simply scaling up P_t left unanswered vital technical questions critical to the effective operation of P_{emd} (U.S. Department of Energy, 2010).

Prototypes Are Value-Added—In the Right Context

Examining defense acquisition programs using the P_s to P_{emd} spectrum and the idea of D_o and D_c reveals that virtually all programs engage in some type of prototyping. The F-35 program is ostensibly a closed design, although its parallel design and manufacturing model means that production aircraft of the current tranche are P_{emd} for later production tranches as design efforts move forward. The DDG-1000 program is also a closed design in that the end configuration was always a surface combatant; however, it brought together a number of subsystem, P_s, prototypes, such as integrated electric drive, a new self-defense radar, low RCS and infrared characteristics, and an advanced gun system for later integration into a coherent whole. Programs use prototypes, but to what end?

In defense acquisition programs, the role of the prototype is either (1) the validation of earlier design decisions, (2) a mechanism for addressing specific technical challenges that are critical to the program, (3) the verification of contract specifications, or (4) enhance competition and support acquisition decisions. It can be argued that programs already do a fair amount of prototyping under (1) and (2) with P_s and P_t efforts; however, the conventional way of thinking about prototyping centers around the P_d and P_{emd} articles that are at the heart of the “fly before you buy” approach. This is not a new concept, but it has recently been reinforced from senior DoD leadership.

In 2007, the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L]) mandated the use of competitive prototyping with the goal of lowering development costs by using competition at the pre-Engineering and Manufacturing Development (pre-EMD) stage (Young, 2007). The missive is notable in that it explicitly defines the role of prototyping within the defense acquisition system. Design teams were to henceforth focus on producing designs for manufacture and production, and competitive prototyping was the means to that end. The instruction goes as far as directing that “large teams should be producing detailed manufacturing design—not solving myriad technical issues.”

The 2007 letter assigned a definitive and explicit role for P_d and P_{emd} prototyping efforts within the defense acquisition systems. The intent was to curb the cost and schedule growth of programs that were spending an increasing amount of time, talent, and funding to mature technologies instead of producing designs for manufacture (GAO, 1999, 2009). The unintended consequence was to marginalize the idea of prototyping, particularly at the P_s level, as a way to inform design decisions.

The 2007 mandate is effective where there are a variety of competitors with the ability to produce P_d and P_{emd} prototypes as part of a competition. Unfortunately, this has not been the case for some decades (Watts, 2008; Watts & Harrison, 2011). The number of companies capable of large systems integration into a comprehensive weapon system is few. Even if there were a healthy number of competitors, the cost of structuring three or more competitions among P_d/P_{emd} articles would be prohibitive (Overstreet, Bates, & Mallicoat, 2013). The following figure illustrates the relative costs of developing prototypes along the P_s through P_{emd} spectrum.

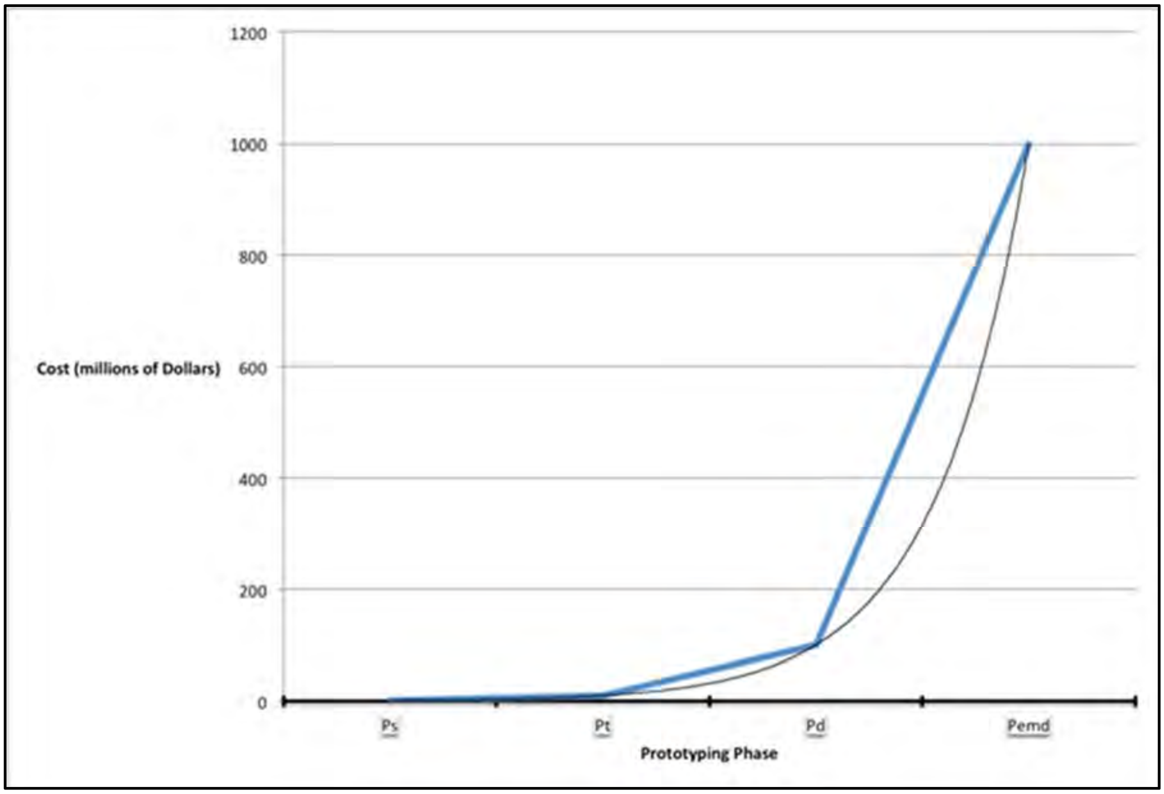

Figure 3. Program Cost Versus Prototyping Phase for Defense Acquisition Programs

Figure 3 indicates an order of magnitude higher cost for each phase of prototyping. Subsystem prototypes are roughly in the millions-of-dollars range, while more complex prototypes at the X- and Y-plane level are \$10–\$100 million-dollar efforts. A P_{emd} competitive prototype that would meet the intent of the 2007 directive would likely be a \$1 billion effort. The estimates are low, although the exact numbers are secondary to the overall shape of the cost curve.

The “fly before you buy” strategy makes sense when multiple vendors can produce P_{emd} articles at an affordable cost. For some defense industrial base sectors, this is impractical, as there is little competition remaining. The tactical aircraft “gene pool” is now so restricted that a P_{emd} type of competition makes little sense and would not effectively inform a competition (Borowski, 2012; Drezner et al., 1992; Lorell et al., 1995).

The 2007 direction emphasizes prototyping as a path to quality manufacturing design and admonishes design teams to avoid “solving myriad technical issues.” This stands the whole nature of prototyping on its head. Design teams are most certainly in the business of solving the technical issues to get to the point of being able to integrate subsystems and assemblies into larger designs. The skills developed in prototyping at the P_s and P_t levels are necessary to produce prototypes at P_d and P_{emd}. The next section discusses how prototyping at the various levels can be used to preserve design skills.

Preserving Design Skills Through Prototyping

The DoD is embarking on a new initiative to establish a technical offset strategy that will maintain the U.S. technology lead in defense systems. Similar to the offset strategies of the 1950s and 1970s, this one is meant to identify critical technology areas where U.S.

dominance is strategically important. It also emphasizes prototyping to maintain the skills of industrial design teams (Weisberger, 2014). This paper has so far discussed how designers work, some proposed attributes of effective design teams, and prototyping in the context of defense acquisition. At what level of prototyping do design teams get the most benefit from the prototyping effort?

Prototyping Benefits to Design Team Attributes

The P_s–P_{emd} and D_c/D_o conceptual framework makes it possible to qualitatively identify which design team attributes are strengthened by various types of prototyping as shown in Table 2.

Table 2. Prototyping Efforts Contribution to Design Team Attributes

	Exp	Arch	Kf	Act	Cur	Size	Eff
P_s							
P_t	+		+		+		
P_d	+	+	+	+	+		+
P_{emd}	+	+	+	+	+	+	+

The rows of Table 2 are the types of prototyping activities and their qualitative contribution to the desired attributes of a design team that produces an operationally realized design, that is, one that is in service and deployed. The columns are the previously identified design team attributes. The yellow cells indicate no strong benefit to a design team attribute, while the green cells represent positive contributions to those attributes.

Not surprisingly, engaging in a P_{emd} effort contributes to the health of design teams, as it exercises or takes advantage of all attributes. It not only exercises the complete design cycle, but also leverages experience, firm-specific knowledge, and the design aspects of production, manufacturing, and logistics engineering required in a deployed system. The P_d level is almost as effective as P_{emd}; however without logistics, manufacturing, or production design required, the size of a P_d team may be much less than for a P_{emd} effort. How much less is a matter of debate. Drezner (1992) estimates that the minimum size of a design team can be as low as 75% of a full production and maintenance team, although this was estimated in the context of a large and competitive tactical aircraft industrial base.

At the P_t and P_s levels, the positive effects on design teams are less because the scope of the effort is lower. The P_t effort is focused on specific technical challenges where the architecture of the end system and the efficiency of the design solutions are secondary. The team size of producing a P_t X-plane article is likely less than producing a P_d Y-plane. Experience, leveraging firm-specific knowledge, and technical currency are positively exercised. Developing P_s articles at the subsystem level likely does not contribute to the attributes of a product design team, but does contribute to the number of partial solutions available to a design team.

Combining the assessments of Table 2 with the cost curve of Figure 3 confirms what is intuitive to most experienced acquisition practitioners—producing increasingly operationally representative prototypes is only achievable through increased costs. The new insight is that the various attributes of an effective design team are increasingly exercised at the higher levels of system integration complexity seen in operationally representative prototypes. The more complete exercise of the design cycle involves multiple types of design expertise, from the conceptual to the logistic and operational.

Extrapolating the trend would indicate that P_{emd} prototyping is the only way to maintain design team viability. This may be true in narrow cases, but it ignores the

conceptual divide between P_s/P_t and P_d/P_{emd} efforts. At the lower levels of prototyping, the end design configuration is secondary to the specific technical challenges addressed. Final design architecture is not known—it is a D_o environment. The design team attributes of size, system architecture knowledge, design team activity, and solution efficiency are less important than experience, firm-specific knowledge, and technology currency. At higher levels, in a D_c environment, the architectural knowledge of the operational configuration becomes a primary consideration.

The effectiveness of P_d/P_{emd} prototypes is the most in the D_c environment of an acquisition program, an idea supported by much of the extant literature (Arena et al., 2006; Borowski, 2012; Coble et al., 2014; Drezner, 1992; Drezner et al., 1992; Drezner & Huang, 2009). It is also the environment addressed by the OUSD(AT&L) 2007 directive on competitive prototyping (Young, 2007). The P_s/P_t efforts are most effective in D_o environments where the novelty of solutions and focus on technical challenges are critical. Historically, the D_o context has been the environment of the technologist and basic science researcher, although many programs have found it necessary to mature key technologies in addition to developing product architectures and designs (GAO, 2006, 2009; Studt, 2006). Three approaches to prototyping and its design team benefits are discussed in the following paragraphs.

The Design Bureau Approach

The simplest way to maintain an existing design team is to keep it working on developing new, or improving old, designs. Congressional funding has often been used to maintain existing production lines and design teams, even when the end article is superfluous. The United States already realizes this situation with the M1A1 Abrams tank. New variants are being ordered to maintain the single production plant in Lima, Ohio, even though the Army has sufficient quantities to meet its needs for the foreseeable future. In many respects it is analogous to the old Soviet approach of ordering another tactical fighter or bomber from the Mikoyan or Tupelov design bureau.

Fully exercising a design team in this way would require design scope and effort resulting in a P_{emd} prototype and its attendant costs. The positive attributes would be that the design team would be working on a closed design with a known architecture with perhaps minimal improvement. The negative aspects are almost the mirror image of the positive. Technical innovation is hampered as designers work with their known and familiar technical solutions in maintaining a closed design. Without adjudication of new requirements or system architecture, the end configuration is likely to be very similar to the legacy article.

Technical Demonstrators—A Few Challenging Problems

An alternate strategy is to move down the prototyping spectrum and focus on test articles that address critical technology needs. The implicit assumption is that designers would be working in a D_o environment, where a final system configuration is left unaddressed. Design teams in this type of prototyping are free to utilize innovative partial solutions that address the main technical challenge without the need to compromise with production constraints. In a D_o environment, where there is no dominant legacy system architecture, multiple design teams are free to pursue innovative and potentially disruptive solutions (Christensen, 1997; Clark, 1985; Henderson & Clark, 1990). The cost of developing a technology demonstrator prototype can be an order of magnitude less than that of a P_d or P_{emd} variant.

Prototyping can be cheap, fast, and creative in the permissive D_o environment. The main drawback is that the technical solutions produced may have little alignment with defense needs and requirements. Prototypes at the P_s level produce optimized designs for

the subsystem technical challenges. They represent partial solutions that are the building blocks for system designers, but are rarely comprehensive to the point of underpinning entire system architectures. Integrating up to the P_t level makes for a more comprehensive partial solution, but one that may still fall short of supporting a full system architecture, as was seen in the F-117 and Manhattan Project development efforts.

Architectural Prototyping

Simply maintaining design teams or developing unfocused prototypes is not the answer. The former puts existing architectures and thinking in stasis and expends resources against design teams that become increasingly irrelevant as their architectural knowledge becomes dated and stale. The latter is essentially the technology transition problem the DoD now faces with commercial technologies. They represent advanced partial solutions to defense design problems; however, in a D_o environment there is no unifying architectural concept to bridge the "valley of death" between laboratory bench and acquisition program (Beard et al., 2009).

The presence or absence of system architecture determines whether the prototyping activity is in the science/technology domain (a D_o environment) or the acquisition domain (a D_c environment). The presence of an architectural framework facilitates the development of P_d and P_{emd} prototypes as it guides a design team's approach to problem decomposition, depth of analysis, and choice of partial solutions used to arrive at a complete design. The system architecture, like the architecture of a building, possesses design elements and motifs that can be judiciously extended and modified to extend the utility of the architecture. With dated architectures there is little flexibility to pace the threat and operational environment; the design team is challenged to improve the design without breaking the system architecture.

Design teams can remain technically current and active by considering the design and prototyping of the architectures themselves. Developing and prototyping system architecture, rather than a specific design, offers the design team the opportunity to integrate state-of-the-practice technology in new ways that meets overall capability requirements. The quality metric of a prototype architecture would be its ability to deliver capability as its base technologies change over time. A suitably flexible architecture would yield a number of specific designs depending on the design team selection of specific P_s partial solutions chosen by the design team.

This architectural prototyping is similar to P_t prototyping; however, it works on a higher level than that of a product design. For example, the F-117 prototype integrated existing technology in support of a low-observable design. An architectural prototype would develop a low-observable architecture broader than the design of a manned tactical fighter. Designers would consider component technologies and their associated technology trajectories to avoid point solutions with limited futures. Different plan forms and technologies would be compared as part of a low-observable architecture that offered varying levels of stealth capability.

Harmonizing Prototyping Approaches

The prototyping approaches discussed exercise design skills but at different levels. P_s and P_t efforts operate at the low to middle region of the design scale, while P_d and P_{emd} efforts work most effectively at the more comprehensive end. Prototyping at the subsystem and tech demo level are the basic elements of more complex systems, relatively cheap to achieve, but unfocused without an overarching architecture. The more complex prototypes are orders of magnitude more expensive.

The most ephemeral skill maintained by higher order prototypes is the integrative facilities of the design team and its ability put together complex systems into a unified whole. Prototyping architectures, rather than an individual design, can provide the design team with developing a capability architecture that can accommodate a number of specific designs that meet the same capability requirement.

Prototyping architectures place more emphasis on general- and system-specific, rather than firm-specific, knowledge. This would seem to put industrial design teams at a disadvantage, but there is no reason to believe industry, with the proper incentive, could not engage in more abstract design activities. Designing at the architecture level removes some of the intellectual property issues that have become increasingly common with government and industry cooperation. Expanding the number of potential architectures multiplies the number of potential designs and design solutions, exercises many of the design skills noted in this paper, and makes for a richer design environment at the beginning of acquisition programs.

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